Accuracy of the laser-launched flyer technique for measuring equations of state

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Abstract

The TRIDENT laser was used to launch copper flyers from coated PMMA substrates. The flyers were 55 and $250\,\mu$m thick and $4\,$mm in diameter. Using a laser pulse $\sim 600\,$ns long, and an energy of 10 to $20\,$J, speeds of several hundred meters per second were obtained. The deceleration of the flyer was measured on impact with a PMMA window. Given the equation of state and optical properties of PMMA, the deceleration allowed points to be deduced on the principal Hugoniot of copper. The points deduced were in good agreement with the published equation of state for copper, suggesting that there was no significant preheating of the flyer or other systematic effects which might reduce the accuracy of equation of state measurements.
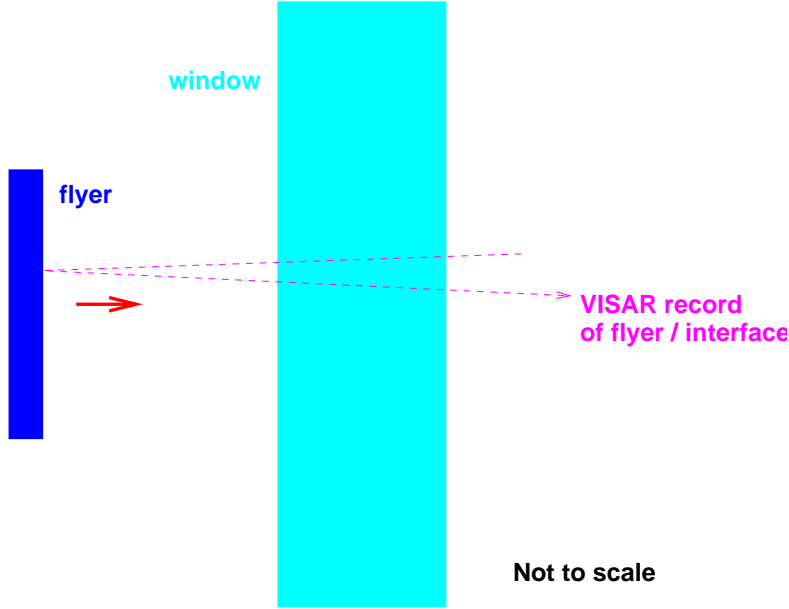
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Figure 1: Schematic of flyer impact experiments.

1 Introduction

This work was performed in support of LDRD experiments in which it is desired to measure the equation of state (EOS) and strength properties of sample materials. These mechanical properties are to be measured by flyer impact experiments, where the flyer is launched from a transparent substrate by deposited energy from a laser [1]. The flyer speeds were measured by Doppler velocimetry.

Ideally, the flyer should be unaffected by the acceleration process. In particular it should not be heated sufficiently to alter the pressure induced in the target on impact. Here we present the results of the impact of copper flyers on PMMA windows. The EOS of each material is known, so the deceleration observed to occur on impact can be compared with the expected value for a cold flyer.

The experiments reported here were performed at TRIDENT between 18 and 20 December 2001.

2 Experimental method

The flyer on its substrate was spaced off from the impact window, which was a plane disk of PMMA $\sim$2930 μm thick. The complete assembly was screwed together in a target holder. (Fig. 1).

2.1 Target assembly

PMMA substrates were used, coated with $\sim$micron layers of carbon, aluminum, and alumina, in order to absorb the laser energy and insulate the flyer from heating [2].

Copper foils were purchased from Goodfellow Corp; flyers were punched from this stock. The foils had distinct striations and machining marks. We attempted to remove these from the surface to avoid the generation of interference patterns which might interfere with the laser velocimetry measurements, by polishing the surface manually using diamond paste. This was only partially successful.

Each flyer was attached to its substrate with five-minute epoxy, the flyer being pressed down to minimize the thickness of the glue layer. In the limited time available, we did not measure the thickness of the glue bond.

2.2 Diagnostics

We used the Johnson line VISAR and a point VISAR to measure the velocity history of the flyer. The input/output optics were as described previously [2].

Lenses were used to image the target through the VISAR (i.e. passing a collimated beam) to the slit of the streak camera. Timing markers were incorporated on the streak record, at intervals of 200 ns. As before, the probe laser was made to produce a long ($\sim$1.5 μs) pulse to be able to capture the acceleration and impact of the flyer. The fringe constant of the VISAR was computed [3] from the thickness of the delay element (9.970" of BK7 glass). The dispersion of the glass was determined at the wavelength of the probe laser by fitting a straight line to points sampling the variation of refractive index with wavelength [4]. The fringe constant deduced was 216 m/s for a probe wavelength of 660 nm.

2.3 Drive beam

TRIDENT was operated in long-pulse mode, as in the previous flyer work [2]. The drive pulse was chosen to be $\sim$600 ns long (full width, half maximum). The pulses generated were asymmetric in time, with a long tail.

An IR random-phase plate (RPP) was added to smooth the beam; this made a significant difference to the spatial uniformity. The beam optics were arranged to give a spot $\sim$4 mm in diameter on the substrate. The drive energy was quite low, so no RPP shield was included. The RPP collected a small amount of debris from the substrate, but was not significantly damaged. The surface of the RPP became misty after a couple of shots; this did not degrade the energy imparted to the flyer to any appreciable extent, and no larger-scale damage was observed after repeated firings through the same region of the RPP (as was feared if the misty layer absorbed much of the laser energy). We moved the RPP to expose a fresh region once during this series of experiments. The cause of the misting was not determined; one possibility was thought to be the oxidation of a layer of grease collected during storage. However, a surface previously cleaned with ethanol also became misty.

3 Results

Ideally, the velocity history from the surface of the flyer should show a smooth acceleration to a well-established terminal speed, an abrupt deceleration on impact to a speed which remains constant for the time required for the shock wave to travel through the flyer and for a rarefaction to travel back, then a succession of decreasing decelerations as recompactions and rarefactions travel across the flyer (Fig. 2). Before impact, the velocity can be obtained directly from the Doppler shift. Afterwords, light reflects from the sample surface into the compressed window material, so the velocity should be calculated with respect to light traveling at the speed appropriate for the refractive index of the compressed material. The correction is negligible for PMMA.

Impact data for copper flyers were obtained from five experiments. The VISAR records were used to determine the velocity history and flatness of each flyer. The impact of the flyer with the window was recorded, so we were able to measure the flatness directly after several hundred microns of flight. Most of the flyers were still accelerating slightly at the end of the record (Fig. 3). There was some sign of ringing during acceleration, but no sign of shock formation or spall in the flyers.

The flatness of each flyer was measured with the line-imaging VISAR. Apart from a slight lag at the edges, all the flyers were flat to within the accuracy of the data. In most cases, the accuracy was dominated by the uncertainty in spatial wavelength of the fringes.

The point VISAR was used to measure the flyer acceleration and its subsequent deceleration on impact with the window (Table 1). In most cases, after the initial deceleration on impact the velocity traces became more difficult to analyze, presumably because of damage causing changes to the optical properties of the window (Fig. 3). Variations in the signal intensity made it difficult to choose the center of the VISAR polar diagram. For the purposes of this work, little attempt was made to improve the analysis of the later part of the record, because it was sufficient to determine the flyer speed just prior to impact and the initial deceleration on impact. Reasonable effort was made to deduce the velocity history such that the duration of
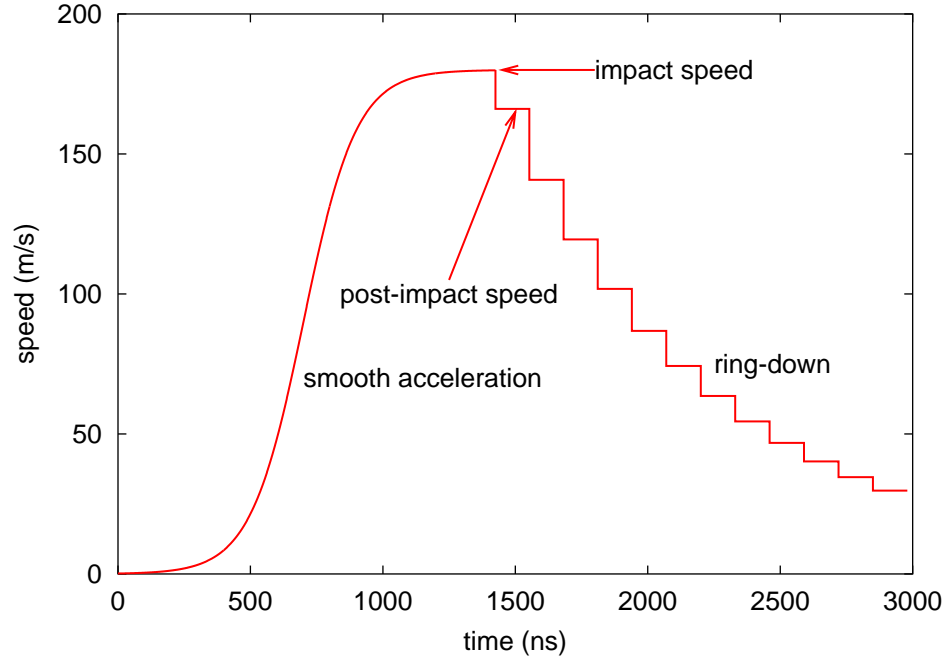
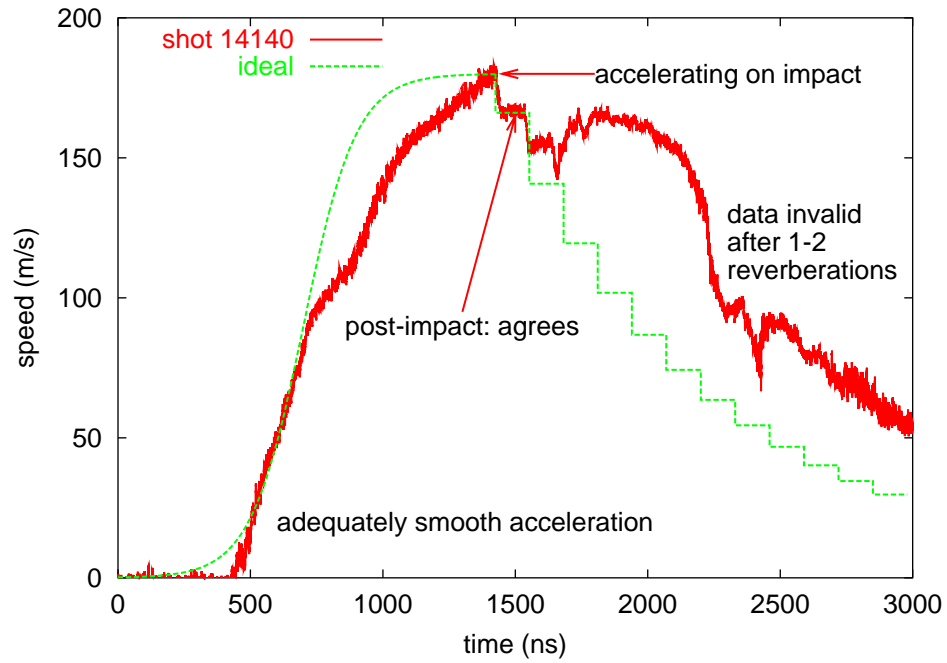Figure 2: Idealized velocity history for flyer acceleration and impact, based on $250\,\mu$m flyer.

Figure 3: Comparison between ideal velocity history and typical record (shot 14140).

Table 1: Copper impact experiments.

Shot	Flyer			Post-impact speed		
	thickness	speed				
	(μm)	(km/s)			(km/s)	
14139	250	153	$\pm$ 2	150	$\pm$	2
14140	250	180	$\pm$ 2	167	$\pm$	2
14147	55	324	$\pm$ 1	297	$\pm$	4
14148	55	573	$\pm$ 2	522	$\pm$	2
14149	55	556	$\pm$ 2	503	$\pm$	2
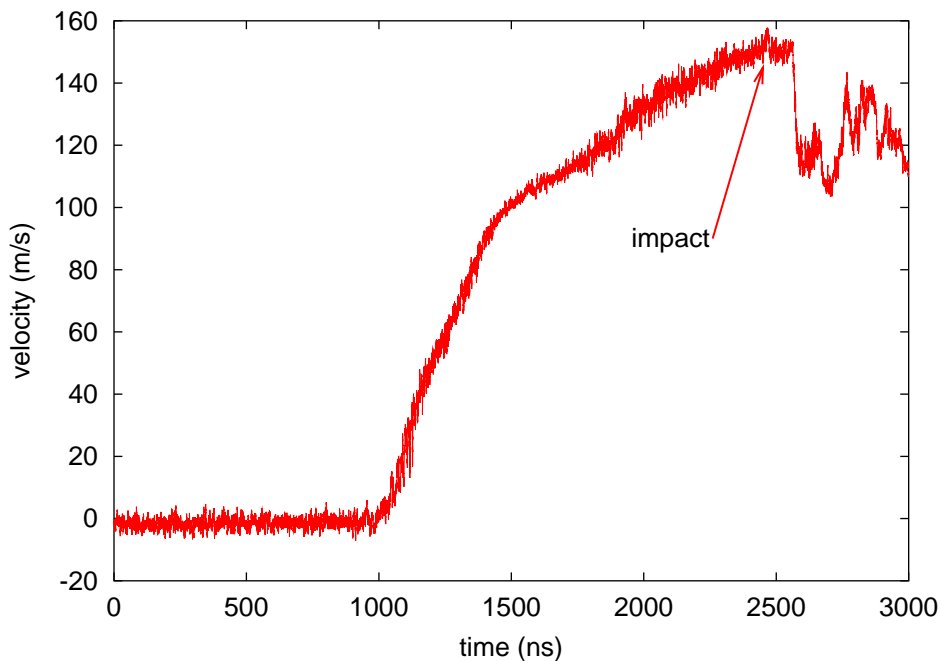
Figure 4: Velocity history for flyer acceleration and impact, shot 14139.

the decelerated plateau could be measured, in order to distinguish the deceleration signature from reflections and noise. (Figs 4 to 8.)

4 Shock Hugoniot

The impact of the copper flyer with the window provided a direct measurement of a point on the principal Hugoniot, with reference to the principal Hugoniot for the window (Fig, 9).

Reference Hugoniots were calculated from published EOS [5]. The Rankine-Hugoniot equations were solved numerically [6].

The pressure regime explored was restricted to ~ 2 GPa and less, because of the low shock impedance of the PMMA. Hugoniot points deduced from impact with the window were consistent with the published EOS for copper. The laser flyer data followed the same trend as published data, but the shock pressures were lower. Apart from the experiments at the lowest and highest pressures, the remaining points fell on the published Hugoniot to an accuracy an order of magnitude better than the estimated uncertainty, which was dominated by the uncertainty in particle speed. This suggests that the random errors may be less than
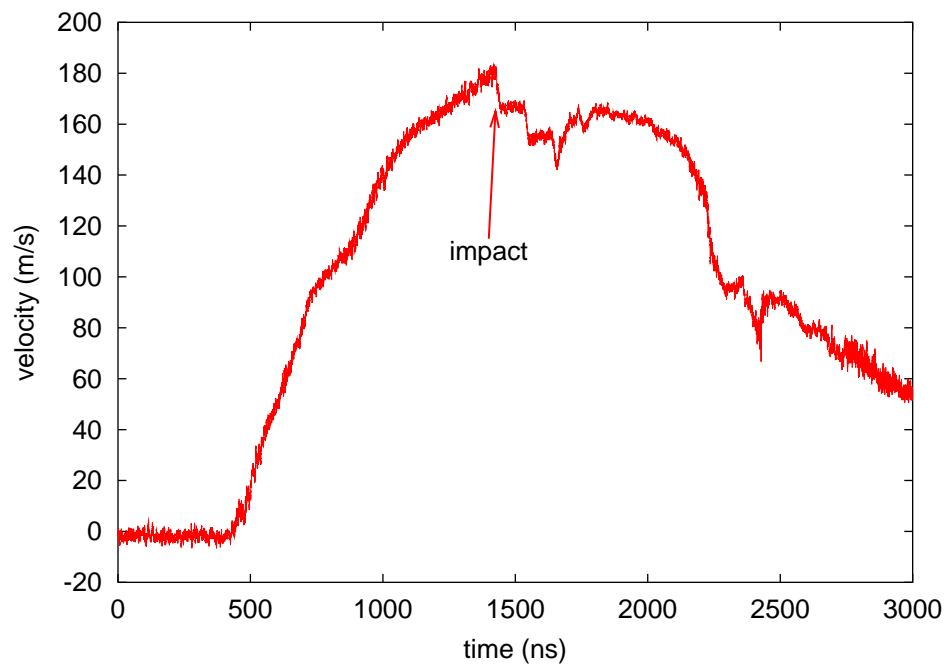
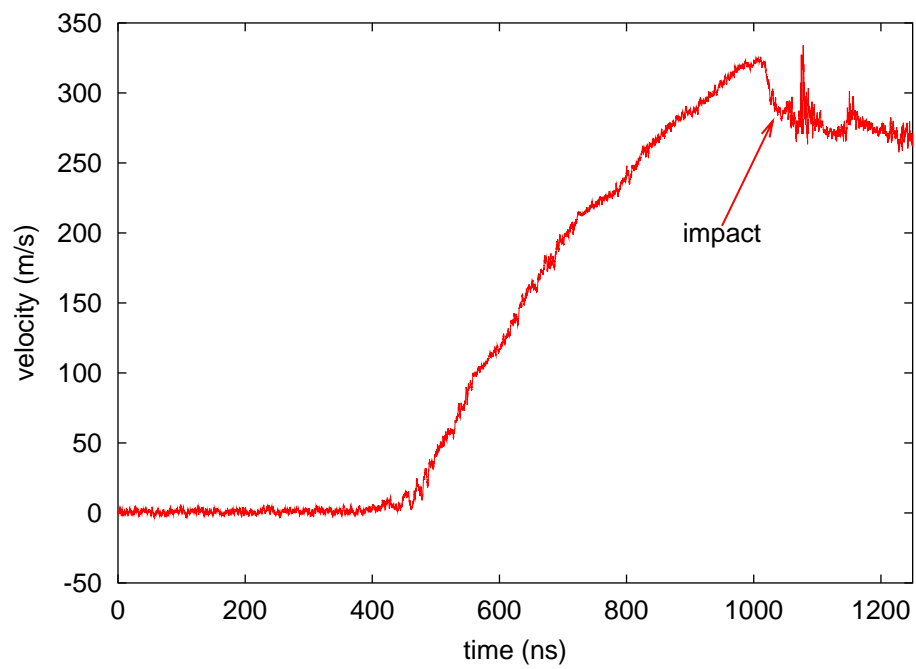Figure 5: Velocity history for flyer acceleration and impact, shot 14140.

Figure 6: Velocity history for flyer acceleration and impact, shot 14147.
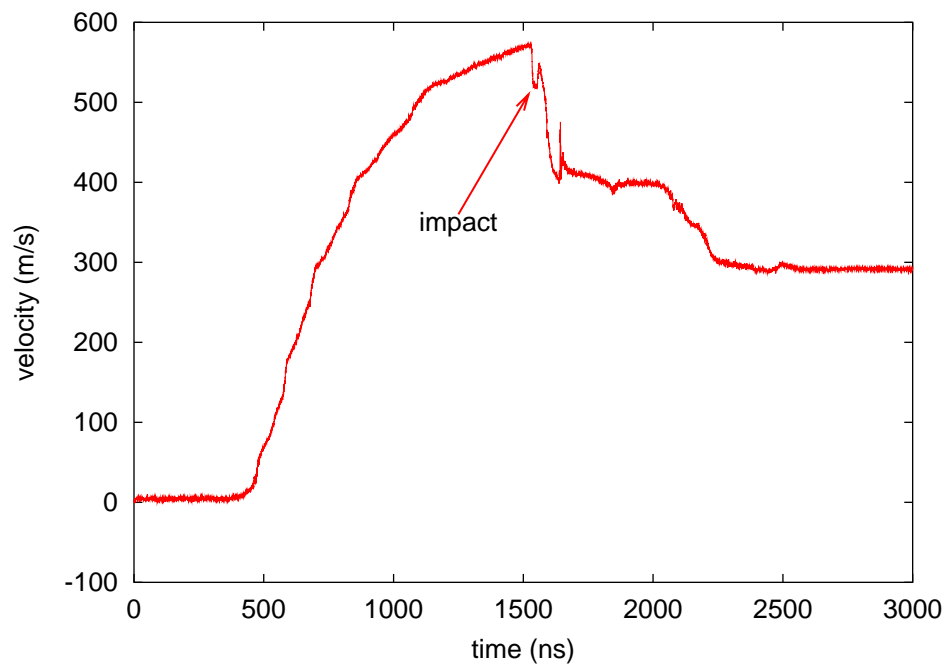
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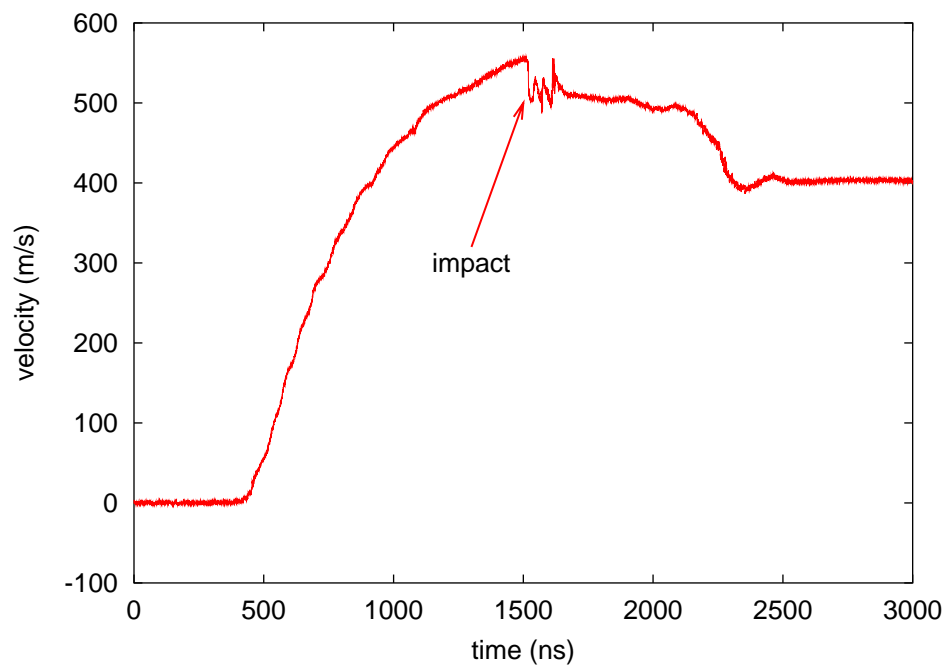Figure 7: Velocity history for flyer acceleration and impact, shot 14148.

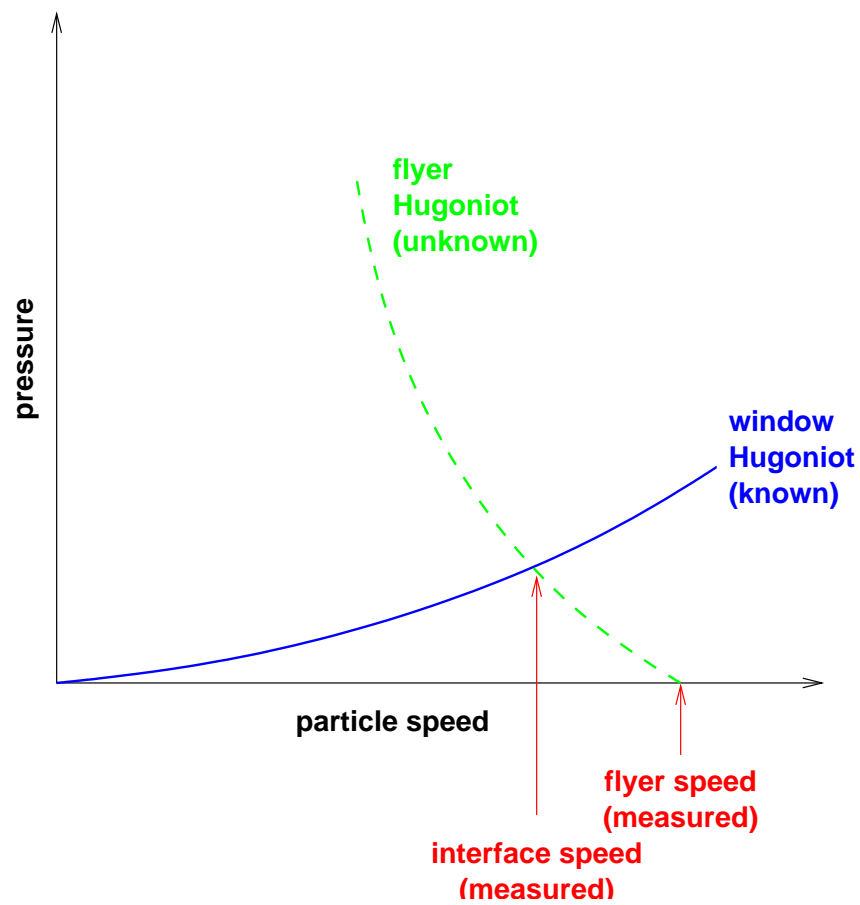Figure 8: Velocity history for flyer acceleration and impact, shot 14149.

Figure 9: Schematic of construction used to deduce Hugoniot point from window impact data.
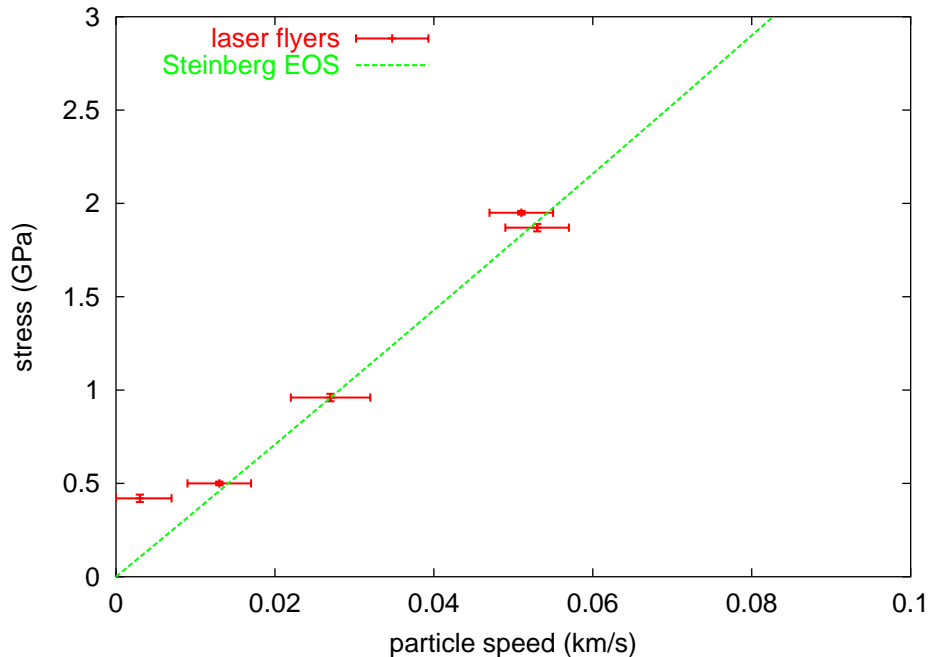
Figure 10: Flyer Hugoniot points compared with Hugoniot from published equation of state.

the conservative estimates used here, but that there are sources of systematic error which do not manifest themselves in every experiment. (Figs 10 and 11.)

5 Conclusions

Experimental Hugoniot points were obtained for copper, by measuring the deceleration of a copper flyer on impact with a PMMA window. The Hugoniot points were generally in excellent agreement with the published equation of state for copper. This indicates that the flyers were not heated by the acceleration process to a degree where the state was significantly affected. The accuracy obtained in this particular case was $\pm 0.005\,\mathrm{km/s}$ and $\pm 0.02\,\mathrm{GPa}$.

Several improvements could be made in future experiments. It is desirable to have a more reflective finish for any surface to be viewed through a window. This is probably preferable to adding an anti-reflection coating to the window, as the layers of different refractive index would affect the Doppler shift after impact. A reasonable compromise would be to coat only the side of the window facing toward the VISAR. It would be easier to determine the Hugoniot over a range of pressures from window impact experiments if a range of different windows were available to cover a range of different shock impedances.

Acknowledgements

References

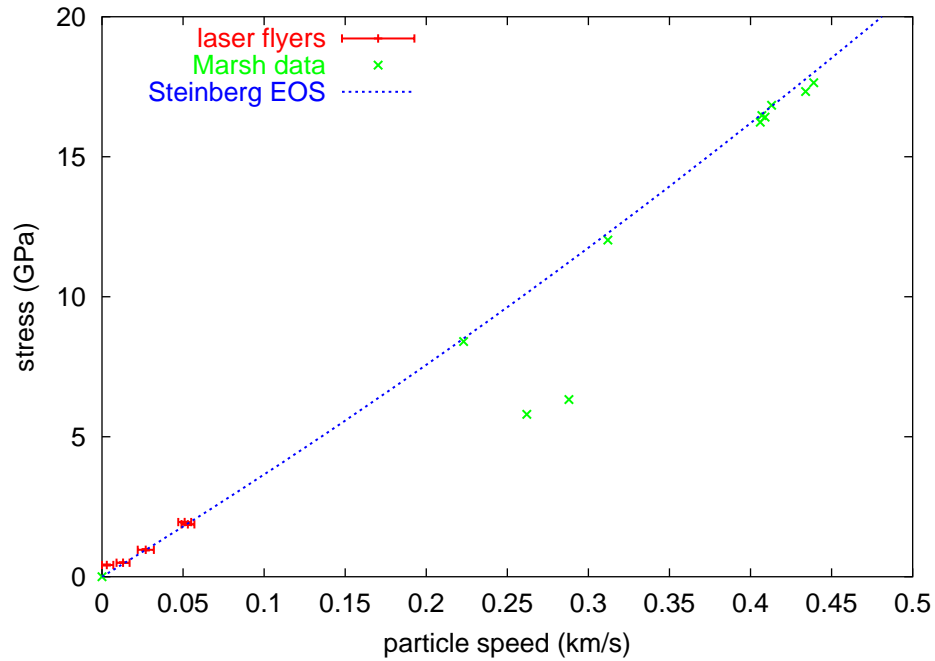[1] D.C. Swift, *Laser-launched flyers from PMMA substrates*, LA-UR-02-0905 (2002).

Figure 11: Flyer Hugoniot points compared with published experimental data.

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[3] D.C. Swift, *Derivation of VISAR fringe constants*, LA-UR-02-0904 (2002).

[4] Melles Griot catalog, Melles Griot Corp (2001).

[5] D.J. Steinberg, *Equation of state and strength properties of selected materials*, Lawrence Livermore National Laboratory report UCRL-MA-106439 change 1 (1996).

[6] 'ELECTRA' software and manual, Wessex Scientific and Technical Services Ltd (2000).